STUDY OF ANOMALOUS MINE BLASTS

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ABSTRACT

The Altai-Sayan mining region located east of Novosibirsk, Russia, comprises over 72 mines which are located between 7 and 559 km from the International Monitoring System (IMS) primary 3-component station ZAL. We have origin time and location estimates of 853 blasts that have occurred in this trend between 1/1/1995 and 6/30/2000. The mines are known to use millisecond delay-fire blasting and had explosive yields ranging from < 10T to > 500 T. We are currently analyzing the range dependence of seismic waveforms from these blasts to prepare for the use of a correlation method to associate individual mine blast recordings with a specific mines and to look for detonation anomalies. Detonation anomalies are of particular interest as the simultaneous release of a significant explosive yield within a routine mine blast shot sequence might be confused with a clandestine nuclear test.

Recent advances in the simulation of seismic signals from delay-fired mine blasts make it possible to study the effects of these complex events provided that ancillary data on the events under study and the medium through which the energy propagates to the receivers are available. Our focus thus far has been on the collection of ground truth data on blasts in the Altai-Sayan region and the crustal structure. We are currently assessing the accuracy of the data and arranging the collection of more complete data in the future.

We have observed surface waves at the Kyrgyz broadband seismic network (KNET) that have been produced by large mine blasts in the Altai-Sayan trend. We are currently assessing the utility of the dense KNET for characterizing sub-kiloton mine blasts from mid- to far-regional range.

KEY WORDS: Altai-Sayans delay-fire mine blasts, detonation anomaly, ground truth data, waveform correlation

OBJECTIVE

Our primary objective is to enhance our ability to identify mining explosions using seismic recordings made at any regional distance and to detect, and characterize, any unusual, large, simultaneous detonations these events might include. The mining technique of choice, worldwide, is delay-firing. Although significant mining operations exist worldwide, we study blasts in the Altai-Sayan region (Figure 1). This mining trend is located east of Novosibirsk, Russia and consists of over 72 open-pit and underground mines. This is the most active mining region in Russia and has produced over 800 significant blasts that have been recorded seismically and located since the beginning of 1995. A much larger number of small blasts have occurred in the trend. We study blasts that have been recorded by IMS stations and by the dense Kyrgyz broadband seismic network (KNET). The mines are located within 6° of the IMS primary 3-Component seismic station ZAL and are12 to 13° from KNET. We study this region because of the frequency of large blasts, the variety of blasting methods employed, the presence of surface and underground mines and the existence of natural seismicity in the near-vicinity of the mines, all within close proximity of ZAL.

Briefly, we are interested in characterizing routine mine blasts in this region to improve our ability to distinguish these events from earthquakes and mine blasts that include significant detonation anomalies. For this purpose, we are planning to use a waveform correlation technique applied to ZAL recordings. We

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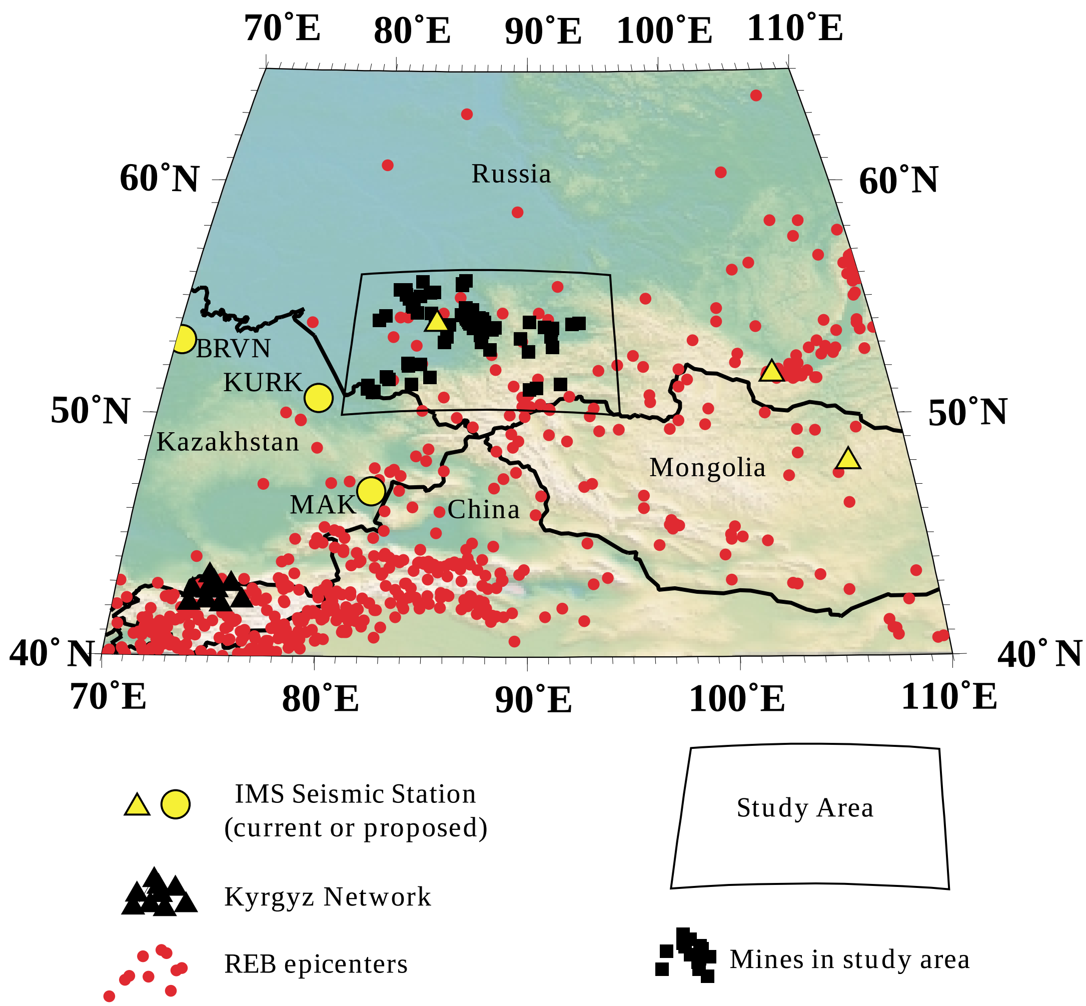

Figure 1. Seismic events reported in the reviewed event bulletin between 1/1/95 and 2/20/2000 are plotted with seismic stations in Central Asia near the study area. The study area includes 72+ surface and underground mines in the Altai-Sayan mining trend.

will also examine spectral rugosity and enhanced surface waves that result from delay-firing. We are collecting ground-truth information on large blasts in this region and information on crustal structure to prepare for modeling of the blasts. We are assessing the accuracy of the ground-truth information. As many of the IMS recordings of mine blasts will be made at mid- to far-regional range, we will also assess the utility of low-frequency seismic signals for characterizing mine blasts. For this purpose, we will use IMS and KNET data.

RESEARCH ACCOMPLISHED

Introduction

The Reviewed Event Bulletin (REB) published by the prototype International Data Centre (PIDC) indicates that large mining explosions are commonly detected by International Monitoring System (IMS) seismic stations at all regional distances; some are seen teleseismically. Khalturin et al. (1997) surveyed over 30 regions worldwide and found that 100 to 200 blasts each year have a magnitude greater than 3.5. Some mining explosions will be difficult to distinguish from single explosions and earthquakes.

Large mining explosions are problematic not just because these events will trigger the IMS, but these large explosions offer a means to obscure nuclear tests. This evasion scenario is particularly troubling because

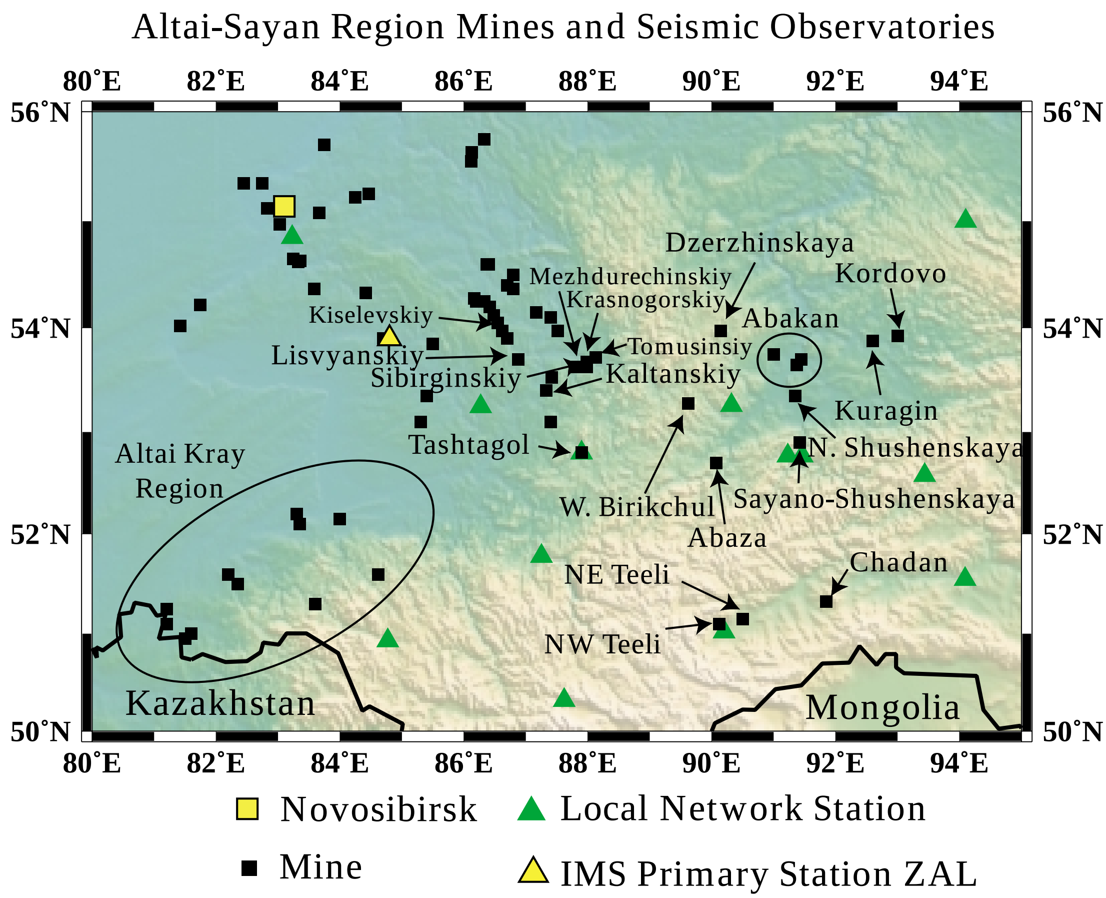

FIgure 2. Mines located in the Altai-Sayan mining region. Most mines are located to the east of Novosibirsk, Russia and are located less than 559 km from the IMS primary 3-component seismic station at Zalesovo. Blast yield and frequency are strongly dependent on the area of the mine. The Altai Kray mining region is responsible for relatively few, small, blasts. Significant blasting is common in the Kuzbass region near the center of the map. The mining region is monitored closely by stations in the Altai-Sayan Seismological Expedition regional network.

blasting anomalies, in which a large part of a mining explosion shot grid detonates simultaneously, are not uncommon. A nuclear test co-located with an industrial explosion might be entirely hidden or mistaken for a detonation anomaly.

Although some industrial explosions are seen teleseismically, most will not be recorded at this range with an adequate signal-to-noise ratio for detailed study. Most will not occur within near-regional range of any IMS seismic stations. There is a pressing need for discriminants that operate at mid- to far-regional range. Low frequency seismic signals have the potential of facilitating mine source characterization from long range, thus have the potential for reducing the cost of monitoring.

In this paper, we describe mining operations in the Altai-Sayan region, which is located east of Novosibirsk, Russia. We report on our preliminary analysis of seismic recordings made by stations in the International Monitoring System (IMS) and by the Kyrgyz Network (KNET). We will describe our efforts to obtain useful ground truth information on large blasts in this region and on the crustal structure as part of our plan to model the events. We are interested in characterizing mining blasts that appear to detonate as planned. We will also examine events that include significant detonation anomalies.

We present seismic recordings made by stations in the IMS and KNET (located at a range of 12 to 13° from

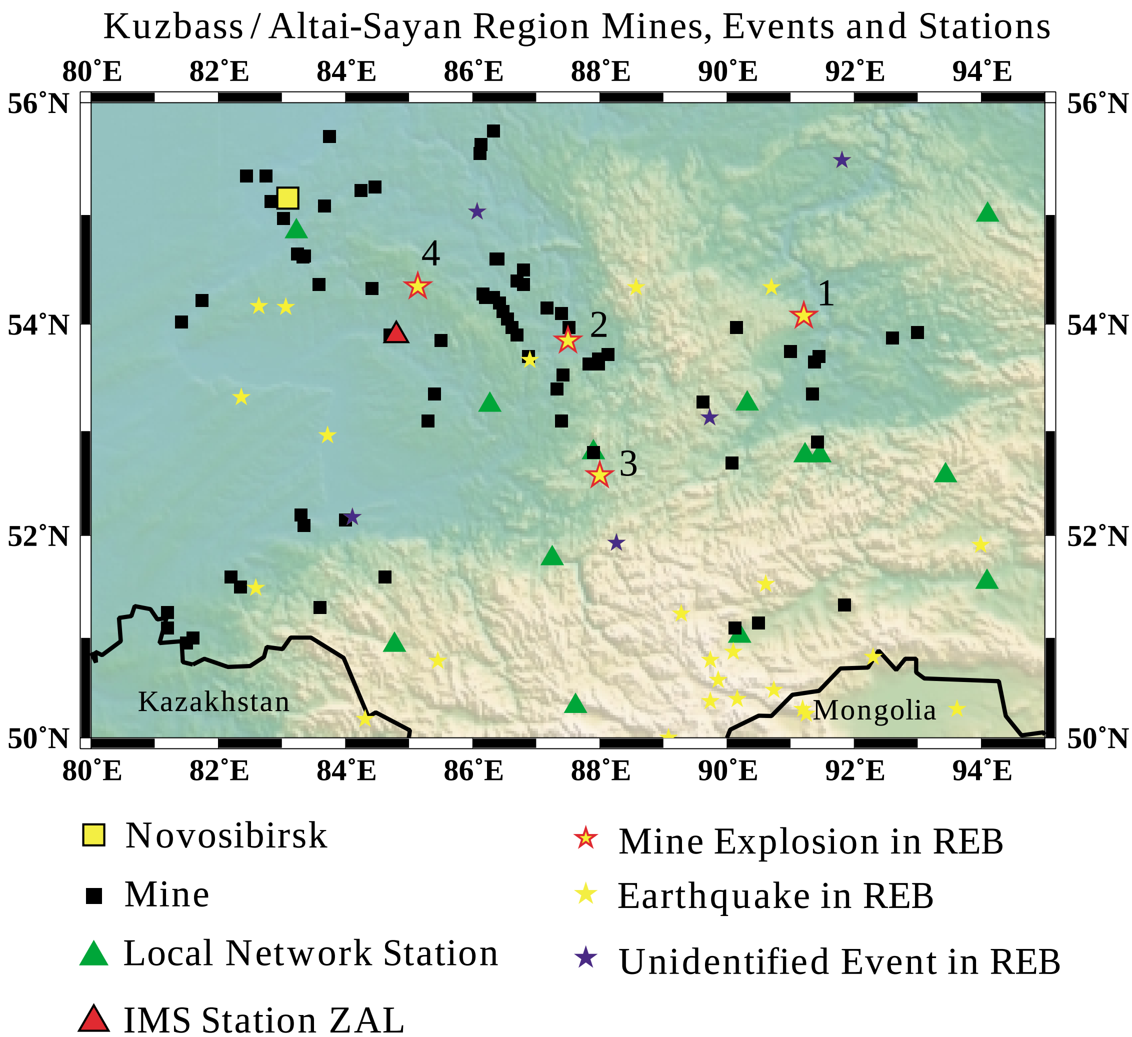

Figure 3. Between 1/1/95 and 2/20/00, 32 events from this region were reported in the reviewed event bulletin. Of these events, 4 are believed to have resulted from mining activity. Some of the REB events are unidentified.

the mines). The KNET data are included in our analysis to determine the utility of a dense network for identifying large blasts from mid-regional range. We also use event locations obtained from the Altai-Sayan Seismological Expedition Network.

Study area

The Altai-Sayan mining region is located in a Paleozoic folded terrain just north of the Mongolian Altai and the Tien Shan (Fotiadi, et al., 1978; Dobretsov, et al., 1995; Zhalkovskii, et al., 1995; Lukina, 1996). The area has remained tectonically active. Over 555 events from the region displayed in Figure 1 were reported in the REB between 1/1/1995 and 2/19/2000. During this time period, 32 of these events occurred in the study area from 50 to 56° N and 80 to 95° E (Figures 2 and 3). The study area includes significant coal mining operations. Mines in the area also produce iron ore, non-ferrous metals (including zinc, copper, lead, molybdenum, and bauxite) as well as precious metals (including gold and silver). We are aware of 72 mines in this region (Figures 1 and 2). There are two large regions of mining activity in the study area. The Kuzbass extends from 53 to 56°N and 86 to 88°E. The Sayans extends from 51 to 54.5°N and 89 to 94° E. The most active mines in the Kuzbass region are in the Mezhdurechinsk area from 53.56 to 53.72°N and 87.68 to 88.10°E. The Krasnogorsky, Tomusinski, Mezhdurechinski, Siberginski and Olzherasski open pits

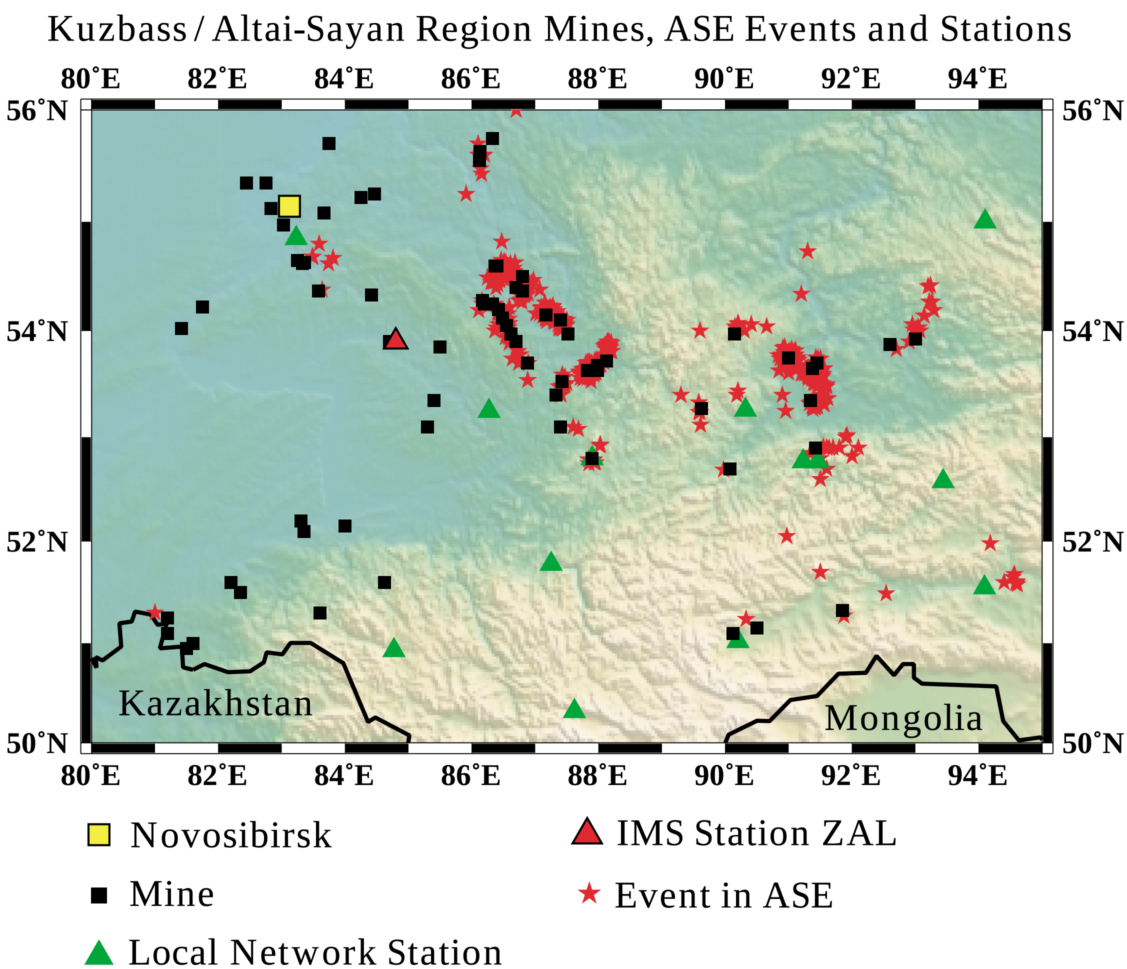

Figure 4. During the time period from 1/1/95 to 2/20/00, over 800 blasts were recorded by the Altai-Sayan Expedition network. The event origins correspond with known mine locations.

are in this area. Each pit is several km long. In the Kuzbass area, over 400 blasts with yield above 100 Tons are known to have occurred in 1999. Of the 28 known mines in the Kuzbass, 26 are open-pit coal mines; two, including Tashtagol, are underground. In the Sayans, there are two active coal open pits near Abakan. These include Chernogorsky and a group of pits collectively referred to as Abakan-2.There are significant construction projects including the Sayano-Shushenskaya hydroelectric power station. In the Sayano-Shuskenskaya area, 1452 explosions occurred between 1990 and 1997 (Dergachev and Filina, 1997).

The IMS primary 3-Component seismic station ZAL and 12 of 17 stations in the Altai-Sayan Seismological Expedition (ASSE) regional network (Figure 2) are located in the study area. The network was deployed by the Altai-Sayans Seismological Expedition of the Siberian Branch of Russian Academy of Science. Each station is equipped with three short-period analog SKM instruments.The magnification is about 30K-50K in the frequency range from 0.7 hz - 15 hz. Some stations also include long period SKD instruments with a pass band between 0.2-18 s. Digital recording equipment was installed at 9 of the sites in 2000. Although seismic recordings from this network are not used in our analysis, source locations and origin times have proved invaluable (Figure 4). Incidentally, the IMS infrasound array, IS46, will be located at Zalesovo.

Five of the events in the study area that were reported in the REB are known to be due to mining activity. Much of the analysis will be based on events that occurred in the same mining trend as the REB events, and were recorded with high signal-to-noise (SNR) at the nearby IMS station ZAL, but did not register on

enough IMS stations to be listed in the REB.

Ground Truth Data

A necessary component of our research is the collection of accurate and detailed information about how, and when, significant blasts have been detonated. Mining blast practice is tailored to local needs and is thus highly variable. During the summer of 2000, Dr Khalturin discussed the collection of ground truth data from mining blasts in the Altai-Sayan region with local experts. Several examples of ground truth information follow:

Table 1: Basic ground truth information

Year	Yr	Dy	Hr	Mn	SS.S	Lat	Long	Energy Class	Mine	Misc Information	
1999	07	20	07	22	37.6	53.63	86.86	8.1	Listvyan.	Y-239t	35 msec
1999	07	23	06	13	03.5	53.59	87.45	8.7	Kaltansky	Y=244t	
1999	08	11	08	06	33.5	53.68	87.80	10.3	Sibirginsky	Y=549t	35 msec
1999	09	01	07	31	14.3	53.69	87.88	8.2	Krasnogor.	Y=173t	L=467 m
1999	09	28	08	08	28.9	54.07	86.49	9.0	Kiselevsk	Y=224 t	50 msec

Y is total shot yield, L is length of row and, for some events, the inter-shot delay is given.

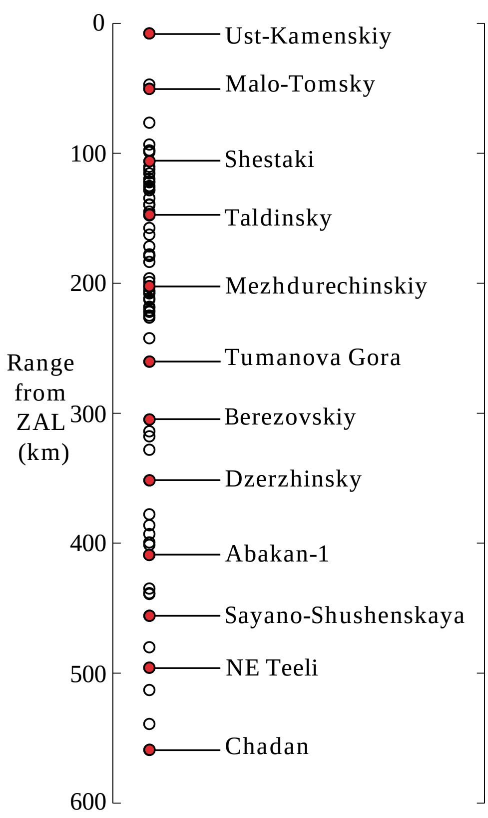

Figure 5. The 72 known mines in the A-S trend are located less than 559 km from the IMS station ZAL. Selected mines at ~ 50 km intervals are highlighted. Most blasting is due to mining activity. The Sayano Shushkenskaya blasts are for construction of a hydroelectric dam.

Much more detailed information is available for a small subset of the blasts. Information pertaining to the 549 ton blast that occurred in the Sibirginsky open pit coal mine on August 11, 1999, was particularly detailed and indicative of the level of detail we might expect in the future. The Sibirginsky mine includes one pit that is ~ 14 km long and 1.5-2 km wide. The event was recorded at 10 stations in the ASSE network and was assigned a coda wave magnitude of 3.2, an origin time of 08:06:33.3 UT and a geographic location of 53.62° N, 87.85° E. The ground truth information indicates that this event included 225 holes and a total of 544,948 kg of explosives arranged in 11 rows. The average hole depth was 41.3 m. The interrow delay was 70 msec, intershot delays were 35 msec. Rows were spaced 8 m, adjacent holes were spaced 5-6 m.

The Sibirginsky blast was relatively large, in comparison with other events in this region, but was otherwise not out of the ordinary. The industry standard blast uses 35 msec intershot delays with yields ranging from < 5 tons to > 500 tons. Most mines use multi-row blasting.

The Sayans region (east of the Kuzbass trend) includes surface (open pit) coal mines. Molybdenum ore is mined in Dzerzhinskaya; Sayano-Shushenskaya is a Hydrostation Dam; Abaza, NW Teeli and NE Teeli are underground iron ore mines. Chadan is an open pit coal mine. Multirow blasting is common at the open pit coal mines and the molybdenum ore mines. Multirow grids most commonly involve 20 —50 msec delays between rowsThe Abaza iron ore mine uses multi row grids with 15 msec delays).
The mines in the Altai Kray region produce few large blasts. Typical blasts use 5 to 7 tons of explosives. A few

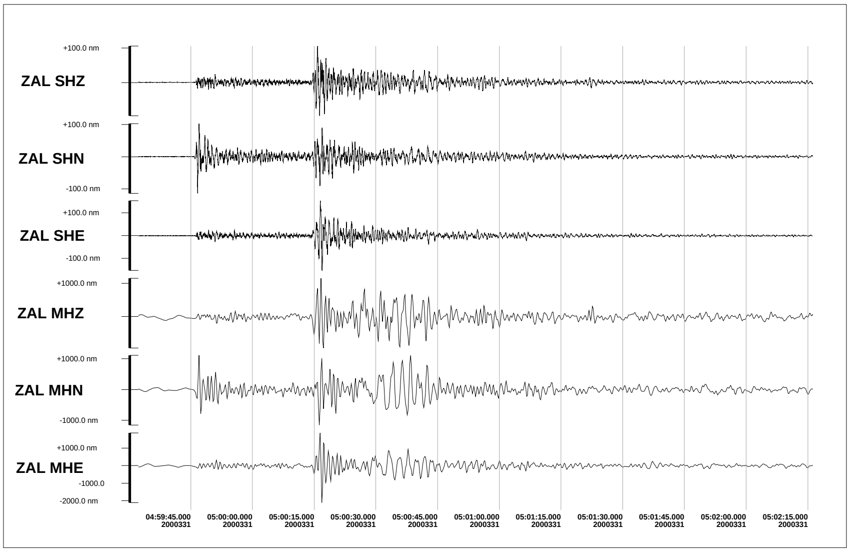

Figure 6. A 690 ton blast occurred in the Tashtagol underground mine on Nov 26, 2000.The MH recordings of this blast made at ZAL reveal a substantial surface wave packet

are greater than 50 tons. The frequency of blasts in each mine ranges from ~ 1/mo to 1-2/yr.

The distances from the mines in the Altai-Sayan region from the IMS station ZAL are given in Figure 5. The trend provides an almost unbroken chain of events from ZAL to > 500 km range.

REB and partially Gr ound Truthed events: Some pr eliminary seismic observations.

The most complete view of seismic activity in the Altai-Sayan trend is given by the ASSE bulletin published by the Altai-Sayan Seismological Expedition (Figure 4). A few of the local mining events are also reported in the REB. Between Jan 1, 1995 and Feb 20, 2000, four events in the REB are known to be mine blasts (ASSE bulletin of explosives).

Table 2. Mine Blasts in study region reported in the REB

Event 1:	1996/01/10 08:14:03.1	54.08N	91.21E	mb 3.2	(Abakan region)
Event 2:	1997/02/20 07:04:00.4	53.85N	87.50E	mb 3.8	(Listvyansky)
Event 3:	1998/02/15 08:51:53.6	52.58N	88.00E	mb 3.6	(Kuzbass)
Event 4:	1998/04/16 04:11:42.2	54.35N	85.14E	mb 3.8	(Abakan region)

Of the 4 events, 2 are known to have occurred in the Kuzbass mining region (Figure 2), the other two occurred in the Abakan mine trend. We have epicentral estimates from the first 3 events from the Altai-Sayan Seismological Expedition (ASSE) bulletin. The average OT difference is 2.0 s. The distance difference average is 55.7 km.

Tashtagol explosion

On Nov 26, 2000, at 04:58:05.8 UT a blast was detonated at Tashtagol (underground) mine at 53.01° N, 87.99° E. The explosive yield has been estimate at 690 tons. The event was assigned an energy class of 9.1 and a coda wave magnitude of 3.1. The details about how this event was detonated are not known yet however it is known to have been delay-fired. ZAL recordings of this event are shown in Figure 6. A significant surface wave packet is evident on the mid-period channels. The short period channels exhibit a clear spectral modulation (not shown).

Kuzbass explosion

A blast detonated in the Kuzbass mine at 2:04 PM local time (07:04 UT) on Feb 20, 1997 was assigned a mb of 3.8 in the REB (and an energy class of 9.2 in the ASSE bulletin). This is the second event listed in

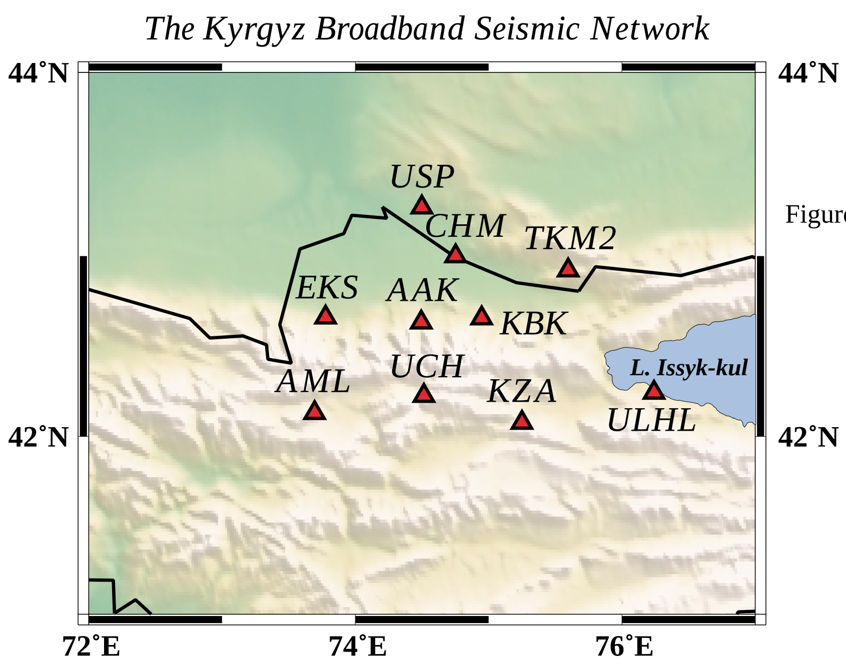

Figure 7. The Kyrgyz broadband seismic network (KNET). The dense KNET comprises 10 stations within an aperture of 200 km.

Table #2. The event was recorded by IMS stations ZAL, HIA, ILAR, YKA, BGCA and DBIC (at 86.06°) and by KNET (Figures 7 and 8). The event was located from 13.47° (TKM2) to 14.90° (AML) from KNET. The arrival at TKM2 at OT+407.4 s gives group velocity of 3.68 km/s.

Planned analysis of ZAL seismic recordings

We study a significant mining region that is covered at near-regional range by one IMS station, and a much greater range by other stations and by the dense seismic network, KNET, in Kyrgyzstan. As the quality, and quantity, of our ground truth data improves, our planned analysis evolves somewhat. We plan to use the high-frequency recordings at ZAL to contrast the spectral rugosity (or roughness) below 10 Hz with that produced by earthquakes from the same region. Our experience with events elsewhere (most notably delay-fired coal mine blasts in Wyoming) is that we should expect significant spectral modulations below 10 Hz, even if the inter-shot delay time is 35 msec. Our experience with Wyoming blasts also leads us to expect enhanced surface waves from the large blasts in the A-S trend. We will examine surface wave amplitudes as a function of event energy class and location using the mid-period recordings at ZAL. We will incoherently stack the > 800 events to define average waveforms as a function of location (or mine) and energy class (e.g. Figure 9). We will compare individual traces to stacked, master, traces to identify detonation anomalies. Our data will be obtained via AutoDRM requests to the pIDC.

Modeling A-S blasts

Once we have adequate knowledge of the crustal structure, and have detailed shot and near-surface information on several blasts that have been recorded well above noise at ZAL, we will attempt MineSeis modeling of the blasts. Physical modeling of normal, and anomalous, mining blasts can be accomplished given the early work of Barker et al. (1990, 93) and McLaughlin et al. (1994) and recent work by X. Yang who has modified the linear elastic algorithm of Anandakrishnan et al. (1997) and packaged it into an interactive MATLAB package (MineSeis; Yang, 1998). The algorithm assumes the linear superposition of signals from identical single-shot sources composed of isotropic and spall components. Both shooting delays and location differences among individual shots are taken into account in calculating delays of the superposition, although the Green s functions are assumed to change slowly so that a common Green s function is used for all the single shots. We used a reflectivity method to calculate the Green s functions. A 1-dimensional velocity model is used (Prodehl, 1979; Anandakrishnan et al., 1997).
An essential step in the modeling of A-S events is the crustal structure. An analysis of seismic recordings

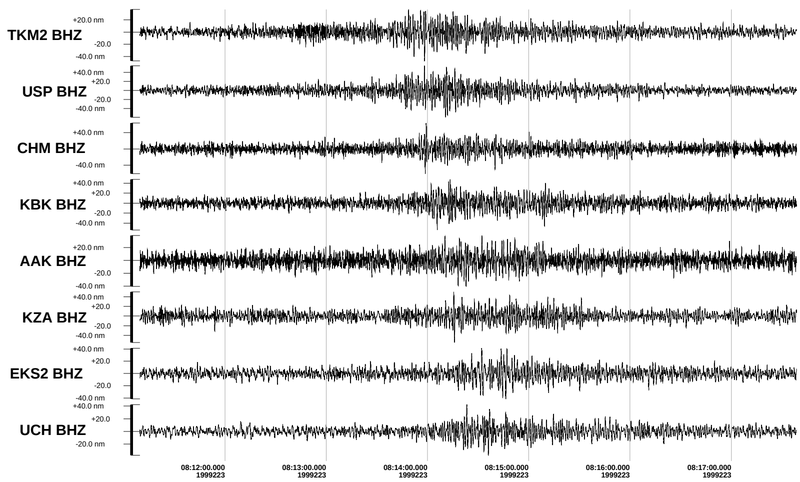

Figure 8. KNET recordings of a surface wave packet produced by a Kuzbass mine blast. that occurred on Feb 20, 1997 .

made by the ASSE network has provided some information on the crustal structure in the Altai-Sayan (Solovyev, et al., 2000). The study of DSS profiles revealsPn velocities ranging from 7.8 to 8.2 km/s. Average upper crustal Pg velocities are ~ 6.0 km/s. Sg velocities range from 3.45 to 3.60 km/s. The depth of the crust ranges from 45-46 km in the northwest corner of the study area to 53-56 km in the southeast.

CONCLUSIONS AND RECOMMENDATIONS

From our preliminary analysis of Altai-Sayan mining events, we believe that there is strong evidence that the methods that have proven to be effective for characterizing large mining events in Wyoming will also be useful in the Kuzbass mining region of Russia. These methods include spectral modulations below 10 Hz and the partitioning of energy between surface and body waves. Most Russian mine blasts produce spectral modulations and surface waves that are recorded by the IMS station ZAL. These observations remain tentative as we do not have enough ground truth information to constrain most events. We have begun a collaboration with Vitaly Khalturin (Lamont) under which we will strive to strengthen communication links between our groups and mining experts in the Kuzbass region.

Observational evidence for the accidental, near-simultaneous, detonation of a large amount of explosives during standard delay-fired explosions comes from other major mining regions. These events have single-fired characteristics and may prove to be problematic in discrimination analysis. The continued study of these unusual events is necessary if we are to minimize the need for on site inspections.

It is important that mining blasts in this significant mining region are properly characterized, despite propagation of the signals across geologically complex structures, to avoid possible false alarms of the monitoring system. A primary thrust of our research will be estimating the frequency and magnitude of detonation anomalies.

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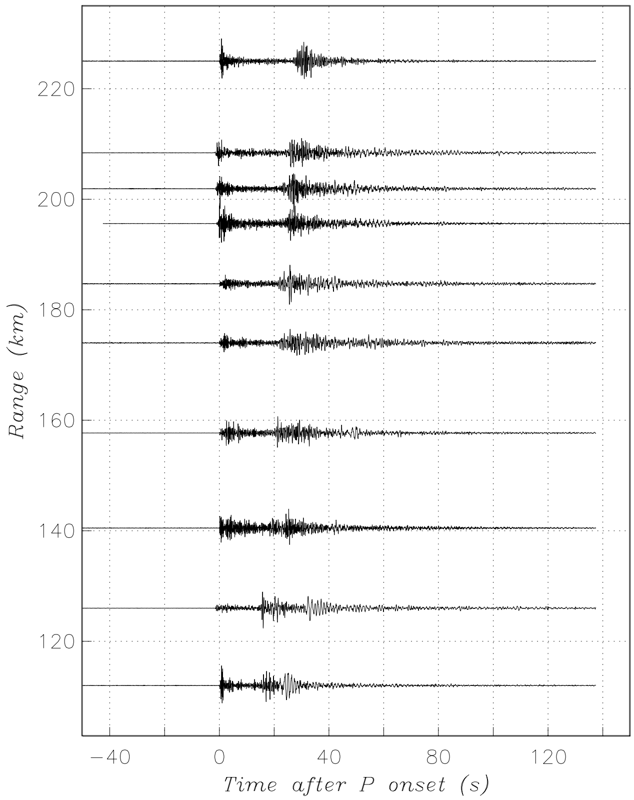

Figure 9. Recordings of Kuzbass mining events made by the short period channel at the IMS station ZAL. Broad spectral modulations are seen most of the events.

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